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EFFECTS OF TROPOSPHERIC AND IONOSPHERIC REFRACTION ERRORS IN THE UTILIZATION OF GEOS-C ALTIMETER DATA

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16. Abstract The effects of tropospheric and ionospheric refraction errors are analyzed for the GEOS-C altimeter project in terms of their resultant effects on C-Band orbits and the altimeter measurement itself. Operational procedures using surface meteorological measurements at ground stations and monthly means for ocean surface conditions are assumed, with no corrections made for ionospheric effects. Effects on the orbit height due to tropospheric errors are approximately 15 cm for single pass short arcs (such as for calibration) and 10 cm for global orbits of one revolution. Orbit height errors due to neglect of the ionosphere have an amplitude of approximately 40 cm when the orbits are determined from C-Band range data with predominantly daylight tracking. Altimeter measurement errors are approximately 10 cm due to residual tropospheric refraction correction errors. Ionospheric effects on the altimeter range measurement are also on the order of 10 cm during the GEOS-C launch and early operation period.					
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SECTION 1.0

INTRODUCTION

One of the primary objectives of the GEOS-C altimeter is the measurement of the sea surface height, on a global scale, relative to the center-of-mass of the earth. From such observations, taken over a period of time, should come a greatly improved ocean geoid along with a better understanding of the temporal sea surface height variations due to tides, currents and other phenomena.

The accomplishment of this objective requires:

1. The calibration and verification of stability of the altimeter height measurement.
2. The determination of the location of the spacecraft relative to the center-of-mass of the earth.
3. The correction of the altimeter measurement itself for those systematic errors which affect it.

One of the error sources which affects all of these elements is propagation error in both ground tracking of the spacecraft and altimeter height measurements. Both the ionosphere and troposphere are sources of error, although the troposphere produces the largest effects on all data at S-Band frequencies or higher. Tropospheric correction procedures available have been investigated [1] and the magnitude of errors from currently available models estimated when meteorological data is available at the tracking site. Because of the expected large extent of GEOS-C tracking by systems which are only slightly affected (C-Band radars, X-Band altimeter), essentially unaffected

(lasers), or have inherent capabilities for corrections for ionospheric effects (TRANET Doppler, Geoeiver) ionospheric corrections are not presently scheduled for the processing of C-Band radar and altimeter data. This report considers the errors introduced in the sea surface height measurement due to tropospheric refraction errors which may be expected on the basis of realistic data availability and quality, and to ionospheric refraction errors when the effects are ignored in the processing of C-Band and higher frequency data.

SECTION 2.0

ALTIMETER MISSIONS AND GEOS-C ORBIT DETERMINATION

The GEOS-C spacecraft will carry an extensive array of tracking instrumentation to support the altimeter and other experiments. This section considers the specific instrumentation which will be used for orbit determination, and the types of altimeter missions which such orbits will be required to support.

2.1 TRACKING INSTRUMENTATION

Instrumentation to be carried on GEOS-C includes:

1. Two C-Band transponders (one coherent, one non-coherent)
2. Laser corner reflectors
3. S-Band transponder (to be used for both direct ground tracking and ground tracking through ATS-F)
4. Doppler beacon

Of the tracking systems utilizing this instrumentation, the lasers are the least susceptible to propagation errors, since tropospheric propagation effects are more correctable at optical frequencies than at microwave frequencies, and ionospheric effects are essentially negligible. However, operational use of the laser systems will be restricted due to the limited number of lasers available, as well as the laser's visibility requirements. All the other systems will be affected to approximately the same extent by tropospheric refraction,

including the effects of water vapor for which it is not possible to accurately correct. Ionospheric effects, on the other hand, should:

- be comparable to tropospheric effects for S-Band tracking (including satellite-satellite tracking since the ATS-F to GEOS-C link is at S-Band)
- be corrected through the use of dual frequency data for TRANET and Geociever Doppler
- be a potentially significant error when uncorrected at C-Band frequencies

Due to its planned extensive use for both altimeter calibration and operational orbit determination, this report will consider all orbit estimation to be made using C-Band data exclusively. This should result in representative tropospheric effects for all orbits for which laser data is not extensively used, and rather pessimistic error estimates for ionospheric errors since the use of either Doppler or laser data should result in reduced sensitivity to ionospheric effects.

2.2 ALTIMETER CALIBRATION

The primary calibration area planned for the GEOS-C altimeter consists of the quadrangle bounded by Bermuda; Wallops Island, Virginia; Merritt Island, Florida; and Grand Turk, B.W.I. Very accurate local orbits are expected to be obtained using a variety of tracking instrumentation, including C-Band radars, located at the corners of the quadrangle. Since the geoid and tides within the area are relatively well known, verification of any bias in the absolute altimeter measurement should be possible.

Three somewhat different types of calibration missions will be performed. Each of these and the type of associated orbit estimation will be briefly discussed.

2.2.1 Single Station Calibrations

Calibrations using a single radar tracking station have the advantage that whenever the pass is near overhead to an island station, an orbit can be determined for the vicinity of the station with the orbit altitude accuracy almost entirely dependent upon the accuracy of the range measurement. In addition, the error in computation of the geoid height at the sub-satellite point to which the altimeter is tracking can be kept small, at least relative to the tracking station, since the distances involved are small for a high elevation pass. The C-Band radars at the calibration sites of Bermuda and Grand Turk are expected to be calibrated in range to the 1-2 m level and, in addition, are due to be co-located with lasers. Orbit altitude accuracies at the sub-meter level are thus expected to be possible in the vicinity of both Bermuda and Grand Turk and calibration missions there are planned. This report considers the effects of propagation errors on such calibrations.

2.2.2 Multi-Station Calibration

The primary calibration mode for the GEOS-C altimeter will be to utilize the entire altimeter data set for the altimeter passing over the calibration area quadrangle. The orbit itself will be estimated with the radars at the four corners tracking down to 10 degrees elevation angle, and the lasers tracking as visibility and signal strength permits. Again, only radar data will be assumed for the propagation error studies.

2.2.3 Stability Verification

One of the larger error sources in altimeter calibration is due to lack of knowledge of the sea surface height within the calibration area. These errors are due primarily to uncertainties in the geoid. Tests of altimeter stability which are independent of geoid errors can be made by comparing sea surface height measurements which are deduced from altimeter measurements made on crossing arcs passing through the calibration area. Actually, such tests can be made any time that the orbit is sufficiently well determined. The calibration area here is of interest, primarily, because of orbits from the large amount of tracking in the area.

Although the tracking geometry will be somewhat different for crossing arcs (one pass will be South-North, the other will be North-South), tropospheric refraction errors should not be significantly different. Ionospheric errors can be drastically different, however, since one pair of crossing arcs will normally be in daytime and the other at night. For this reason, the single station and multi-station calibration simulations outlined above have been performed for both day and night passes. Differences indicate the degree to which ionospheric errors would be expected to corrupt stability comparisons of crossing arcs.

2.3 OPERATIONAL ORBIT DETERMINATION

In order to assure that center-of-mass orbits are being obtained, arc lengths of approximately one revolution or greater are planned for use in obtaining operational orbits for GEOS-C. In addition, the use of a minimum of five tracking stations for each orbit is planned. This should have the benefit of reducing the influence of propagation

errors, assuming a global distribution of the tracking stations. However, some daytime tracking is almost guaranteed and, in practice, operational considerations of "normal" working hours are likely to balance tracking data in the direction of daytime. It is thus particularly desirable to see the effects of propagation effects on global orbits.

Since the maximum orbital arc length which may be used is determined by the geopotential model accuracy, and this may be sufficiently improved either prior to or during GEOS-C operation that much longer orbits may be used, it is of interest to examine propagation effects for arc lengths somewhat longer than one revolution. Accordingly, tropospheric and ionospheric error effects on one day orbits are also considered.

All orbits are considered to be obtained through the use of C-Band range tracking data only and, in general, may thus be slightly pessimistic in view of the availability of some laser tracking data. Propagation error effects on both the orbit estimations, and the altimeter measurement itself, are considered.

SECTION 3.0

PROPAGATION ERROR MODELS

As propagation error, we wish to model the resultant error after operational corrections are made. This section considers operational procedures for tropospheric refraction corrections and the residual error to be expected after such corrections are made. A model for ionospheric error is also discussed.

3.1 TROPOSPHERIC REFRACTION ERROR

Different tropospheric refraction correction procedures are planned for application to ground tracking of GEOS-C and for the altimeter data itself. The two types of data will thus be considered separately.

3.1.1 Tracking Data

Based on the results of Goad [1], a modification of a model by Hopfield [2] is planned for making operational tropospheric refraction corrections for GEOS-C tracking data. This model requires as input surface values of temperature, pressure and relative humidity for each tracking site. The model was chosen over several other models [3,4,5], each requiring the same set of surface meteorological parameters, as giving the best results as compared with ray tracings using radiosonde data taken from Wallops Island, Virginia over a twelve month period. In addition, the selected model gave more satisfactory results at lower elevation angles than any of the other models.

The modified Hopfield model was found to agree with the ray tracings with an rms difference of approximately 2%. To allow for possible errors in the surface meteorological data actually used operationally, the simulations performed for this report have propagated a 3% tropospheric refraction error for all ground tracking stations.

Whenever meteorological data is not available from a tracking site, operational plans are to use a set of surface parameters which reasonably represents conditions from an "average" tracking station. The default parameters which have been adopted are given in Table 1. The pressure variation with altitude has been found to agree well with measured radiosonde data [1] and does not actually pose a potentially large error source. This is not true for temperature and humidity.

To assess the errors which may be incurred when meteorological data from a site is not available, range corrections were computed for hot, wet conditions such as exist at Merritt Island in summer, and for cold, dry conditions such as exist at White Sands in winter. Parameters used as representative of these conditions were:

Merritt Island

$T = 32^{\circ}\text{C}$

$p = 1023 \text{ mb}$

$\rho = 90\%$

White Sands

$T = 0^{\circ}\text{C}$

$p = 890 \text{ mb}$

$\rho = 10\%$

Surface Parameter	Sea Level Value	Variation with Station Height
Temperature	20°C	-6.45°C/km
Relative Humidity	60%	Constant
Pressure	1013.5 mb	Declines consistent with temperature variations

Table 1. Default Surface Meteorological Parameters

Station	Correction (m)		Error	
	Using Met Data	Using Defaults	Meters	%
Merritt Island	2.70	2.44	-.26	-9.6
White Sands	2.06	2.20	.14	6.8

Table 2. Zenith Tropospheric Range Errors for Extreme Climatic Conditions using Default Surface Meteorological Parameters

The zenith range corrections, using the modified Hopfield model and these assumed values of surface meteorological parameters, are given in Table 2, along with the corresponding corrections which would be calculated using the default parameters from Table 1. Since the percentage errors should hold independent of tracking elevation angle, we see that the use of the default parameters can lead to errors of almost 10% in hot, humid climates, with slightly less error in cold, dry climates.

3.1.2 Altimeter Data

The planned procedure for correcting altimeter data for tropospheric effects is to use the same Hopfield model as is to be used for the correction of ground microwave tracking data, with the required input of surface meteorological parameters of pressure, temperature and humidity. As data input, it is planned to use monthly mean values of temperature, pressure and relative humidity as a function of latitude. To assess the error in this procedure, the mean, minimum, and maximum values of these parameters for three selected areas are listed in Table 3. The data, taken from References 6 and 7, is based on records over a period of approximately 100 years. The "mean" values of pressure and air temperature listed are actually median values, while 5% of the recorded pressures and temperatures were below the "minimum" values and 5% were above the "maximum" values.

The tropospheric refraction corrections corresponding to these meteorological conditions are listed in Table 4. The minimum and maximum values were computed by Goodman [6], and all values may be obtained using tables contained in Reference 1. They correspond to the minimum and maximum data of Table 3 and may be somewhat pessimistic since, e.g., maximum relative

Area 392 Location: 45° - 46° N, 58° - 59° W

	JANUARY			APRIL			JULY			OCTOBER		
	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.
Pressure (mb)	984.8	1009.3	1027.4	992.9	1014.5	1029.1	1004.7	1015.3	1024.0	996.3	1015.4	1028.0
Temperature (°C)	-7.2	1.1	5.5	-2.1	1.7	5.5	10.0	14.4	18.3	5.9	10.6	15.0
Relative Humidity (%)	62	87	97	70	86	98	71	92	98	63	83	97

Area 451 Location: 36° - 37° N, 64° - 65° W

	JANUARY			APRIL			JULY			OCTOBER		
	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.
Pressure (mb)	997.5	1016.4	1030.5	1000.6	1015.9	1028.2	1012.1	1020.0	1026.8	1006.3	1017.3	1026.0
Temperature (°C)	9.7	15.6	20.0	11.6	17.2	21.1	23.2	25.6	28.3	19.0	22.8	26.1
Relative Humidity (%)	53.0	77	95.0	53	80	94	65	81	97	55	75	95

Area 521 Location: 23° - 24° N, 70° - 71° W

	JANUARY			APRIL			JULY			OCTOBER		
	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.
Pressure (mb)	1012.5	1018.6	1022.5	1012.6	1017.6	1022.4	1016.3	1019.1	1022.5	1008.6	1014.3	1017.7
Temperature (°C)	21.1	23.8	26.1	22.0	24.1	27.3	26.1	27.8	29.4	25.0	27.3	29.7
Relative Humidity (%)	56	77	95	58	77	95	68	81	94	64	80	95

Table 3. Monthly Average Atmospheric Conditions at the Ocean Surface for 3 selected areas [References 6, 7]

humidity is assumed to occur for maximum temperature which would not normally be expected. Based on Table 4, the expected maximum error from the use of average monthly meteorological conditions would be on the order of 10 cm, or about 4% of the correction itself.

Month	Area	Correction (m)		Meters	Error	
		Max/Min	Mean			%
January	392	2.42/2.27	2.36	-.06/.09	-2.5/3.8	
April	392	2.43/2.30	2.38	-.05/.08	-2.1/3.4	
July	392	2.54/2.38	2.47	-.07/.09	-2.8/3.6	
October	392	2.51/2.34	2.42	-.09/.12	-3.7/5.0	
January	451	2.56/2.34	2.45	-.11/.11	-4.5/4.5	
April	451	2.56/2.35	2.47	-.09/.12	-3.6/4.9	
July	451	2.69/2.49	2.58	-.11/.09	-4.3/3.5	
October	451	2.64/2.41	2.52	-.12/.11	-4.8/4.4	
January	592	2.64/2.45	2.54	-.10/.09	-3.9/3.5	
April	592	2.66/2.45	2.55	-.11/.10	-4.3/3.9	
July	592	2.71/2.53	2.62	-.09/.09	-3.4/3.4	
October	592	2.72/2.49	2.59	-.13/.10	5.0/3.9	
					RSS = 3.9	

Table 4. Altimeter Tropospheric Refraction Corrections and their Errors Based on the Use of Monthly Means

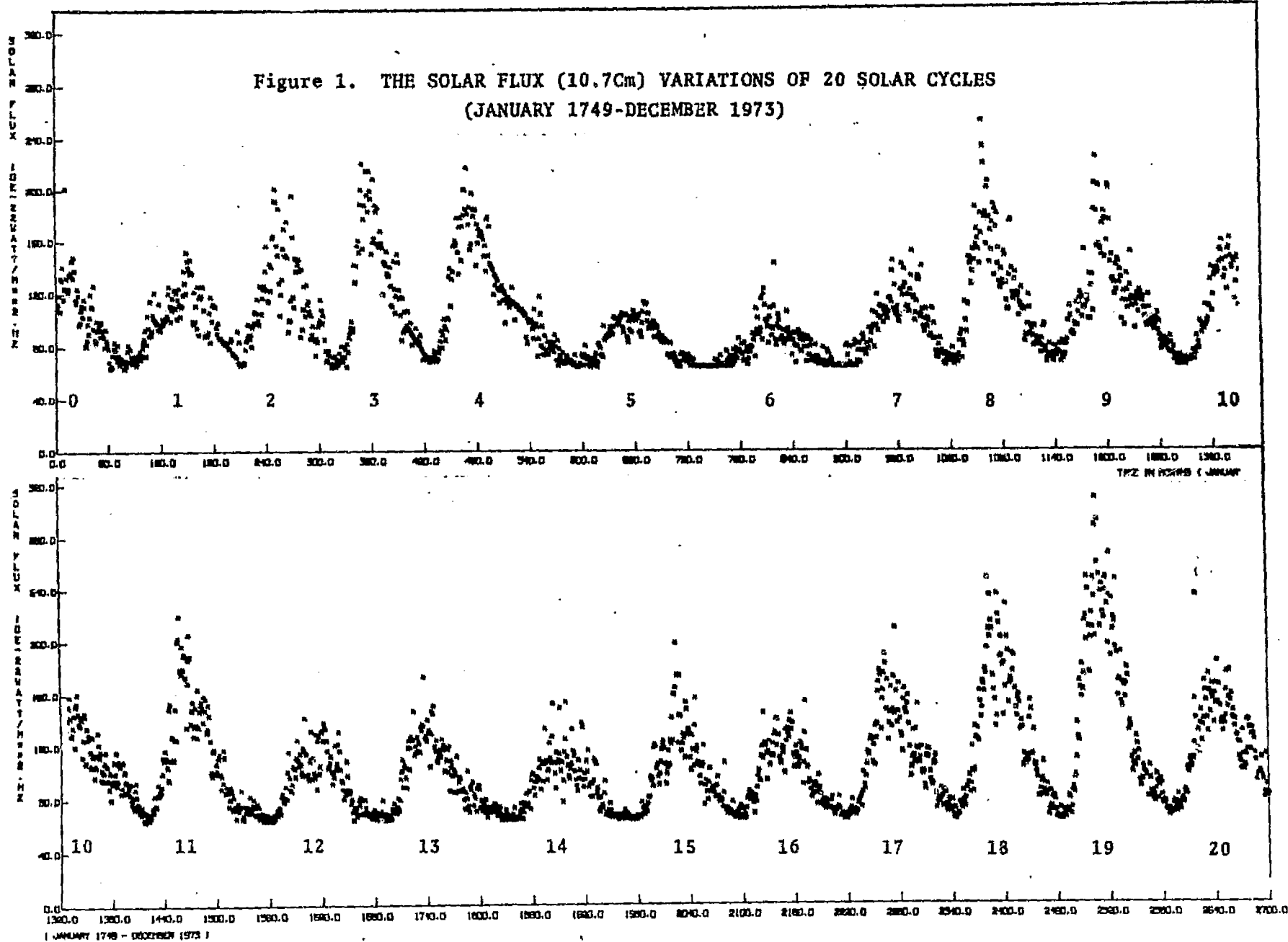
3.2 IONOSPHERIC REFRACTION ERRORS

Since ionospheric propagation effects have normally been less than the overall system accuracy specifications, corrections for ionospheric effects on C-Band tracking have seldom, if ever, been made. The difficulty in making an accurate correction has also contributed to the neglect of the ionosphere in radar data reduction and analysis.

With the orbit accuracies needed for GEOS-C, and the tracking system calibration levels needed to achieve these accuracies, it is desirable to assess the magnitude and characteristics of the errors incurred when ionospheric effects are ignored. To make this assessment, simulations of the altimeter missions described in the previous section have been made using a global ionospheric model developed by Bent [8] and the full ionospheric effect propagated as an error. Although the GEOS-C radar altimeter operates at 13.9 GHz, its operation is still slightly affected by the ionosphere, and ionospheric error propagations were made for this measurement as well as for the tracking system errors as propagated into the satellite orbit.

The effect of the ionosphere on radio tracking is a (linear) function of the total electron content along the ray path from the station to the satellite. The total effect thus depends on the electron density and the satellite position relative to the tracking station (range and elevation angle). Electron density depends strongly on the local time of day and varies linearly with solar flux. The diurnal variation of ionospheric effects will be explicitly illustrated in the error analysis results through the propagation of errors for times of minimum electron density (~2AM) and maximum electron density (~2PM), and variations close to a factor of 10 will be seen. Error propagations for a full satellite revolution, which includes both daytime and nighttime periods, will also be made.

Figure 1. THE SOLAR FLUX (10.7Cm) VARIATIONS OF 20 SOLAR CYCLES
(JANUARY 1749-DECEMBER 1973)



Solar flux has its largest variation with an approximately 11 year cycle, as illustrated in Figure 1 taken from Reference 9. Fortunately for GEOS-C, the current cycle will be at a low during the launch and first year or two of the GEOS-C mission. The simulations made assume a value of 74 (near minimum) for the Ottawa F10.7 cm solar flux value. This value is appropriate for the initial operation of GEOS-C during the second quarter of 1975. Section 5 will consider extrapolations for later years.

SECTION 4.0

ERROR ANALYSIS RESULTS

4.1 METHOD OF ERROR ANALYSIS

All the propagation error analysis results of this section were obtained using an orbital error analysis computer program, ORAN [10], which simulates weighted least squares data processing in a Bayesian batch mode. This type of data processing is utilized by the GEODYN [5] data reduction program and is planned for obtaining GEOS-C orbits. The only error parameters considered were tropospheric and ionospheric refraction, for which errors of 3% and 100%, respectively, were propagated. The altimeter data was considered to be unweighted in the orbital solution, so propagation errors on the altimeter measurement go directly into the sea surface height estimate.

Propagation errors in the ground radar tracking data propagate into the estimated orbit in a manner dependent upon the amount of tracking data, the tracking geometry, the arc length, etc. In the limit of a very long arc and an associated large number of passes of tracking data, propagation errors will produce small errors in the orbit, and any such errors will be largely left in the measurement residuals. For very short arcs, the opposite will be true, with a relatively large effect on the orbit and little evidence of the error in the measurement residuals. Typical measurement residuals due to tropospheric and ionospheric errors for the different types of orbits are also shown below. These indicate the extent to which the presence of propagation errors may be detected during actual data reductions.

4.2 CALIBRATION MISSIONS

4.2.1 Single Station Orbital Solutions

As a typical single station type calibration, a single pass orbital solution was simulated for the Bermuda radar tracking GEOS-C on a North-South pass with a maximum elevation angle of 84° . Both range and angles were assumed to be used in the solution with the data used down to 10° elevation angle and weighted according to

$$\sigma_R = 1 \text{ m}$$

$$\sigma_A = 50 \text{ arc seconds}$$

$$\sigma_E = 50 \text{ arc seconds}$$

Propagation error effects on the orbit are the combined effects on the range and elevation measurement, with the azimuth measurement unaffected.

Figure 2 shows the orbit error due to the assumed 3% tropospheric refraction error. Because orbit and geoid errors grow with distance from the tracking station, the calibration area has been restricted to be within two minutes of PCA. In this region the tropospheric error effect on the orbit is approximately 10 cm. The sign convention for the curve is such that the application of a refraction correction which is too large will result in an orbit which is too low. Since the refraction error should be as likely to be too small as too large, the absolute value of the curve can be taken to be the 1 σ value due to tropospheric refraction error.

Similar curves are shown in Figure 3 for ionospheric effects on the orbit. In order to prevent geometrical effects

FIGURE 2. ORBIT HEIGHT ERROR DUE TO TROPOSPHERIC REFRACTION ERROR

SINGLE STATION, SINGLE PASS SOLUTION

MAX ELEVATION 84°

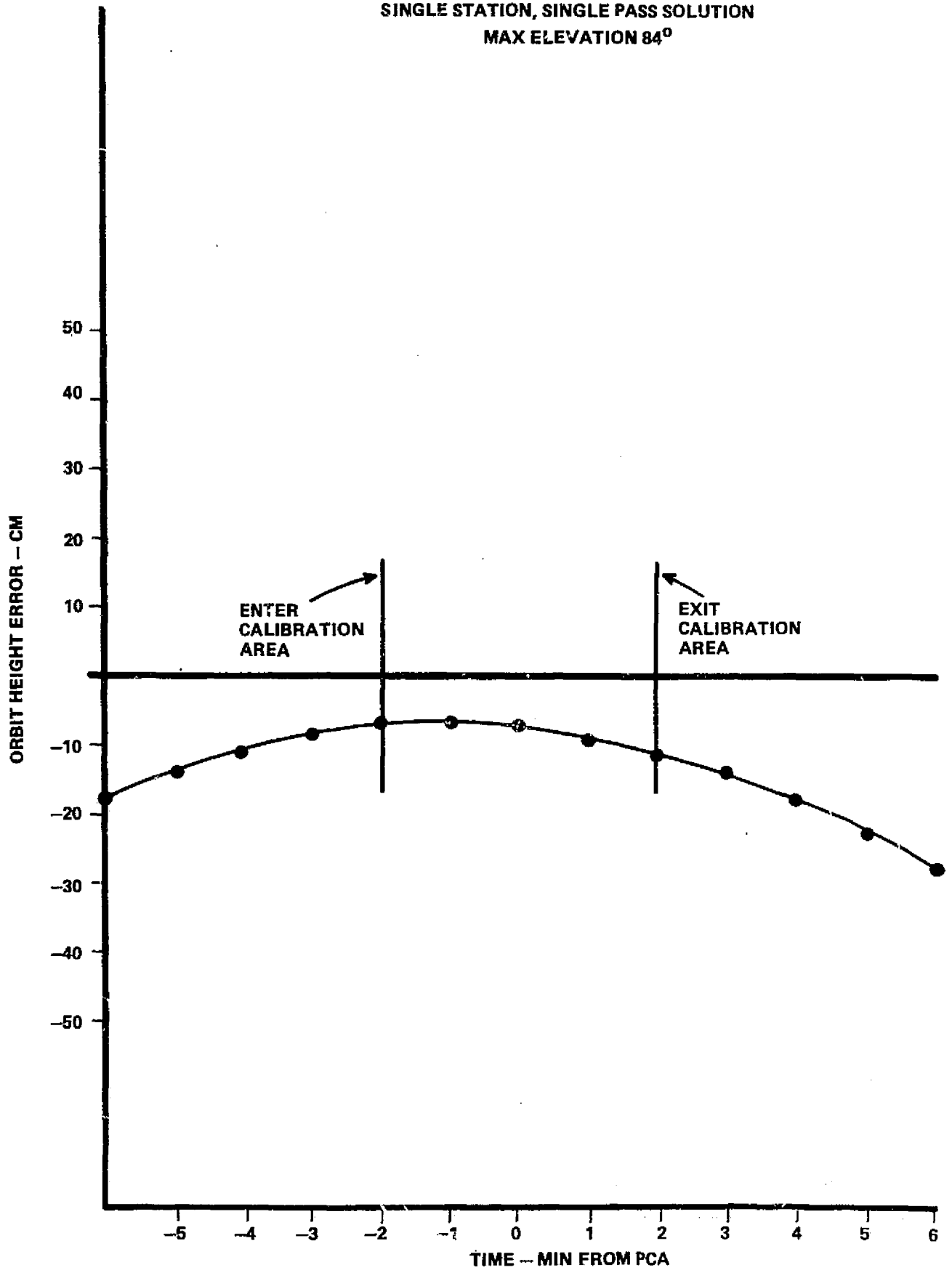
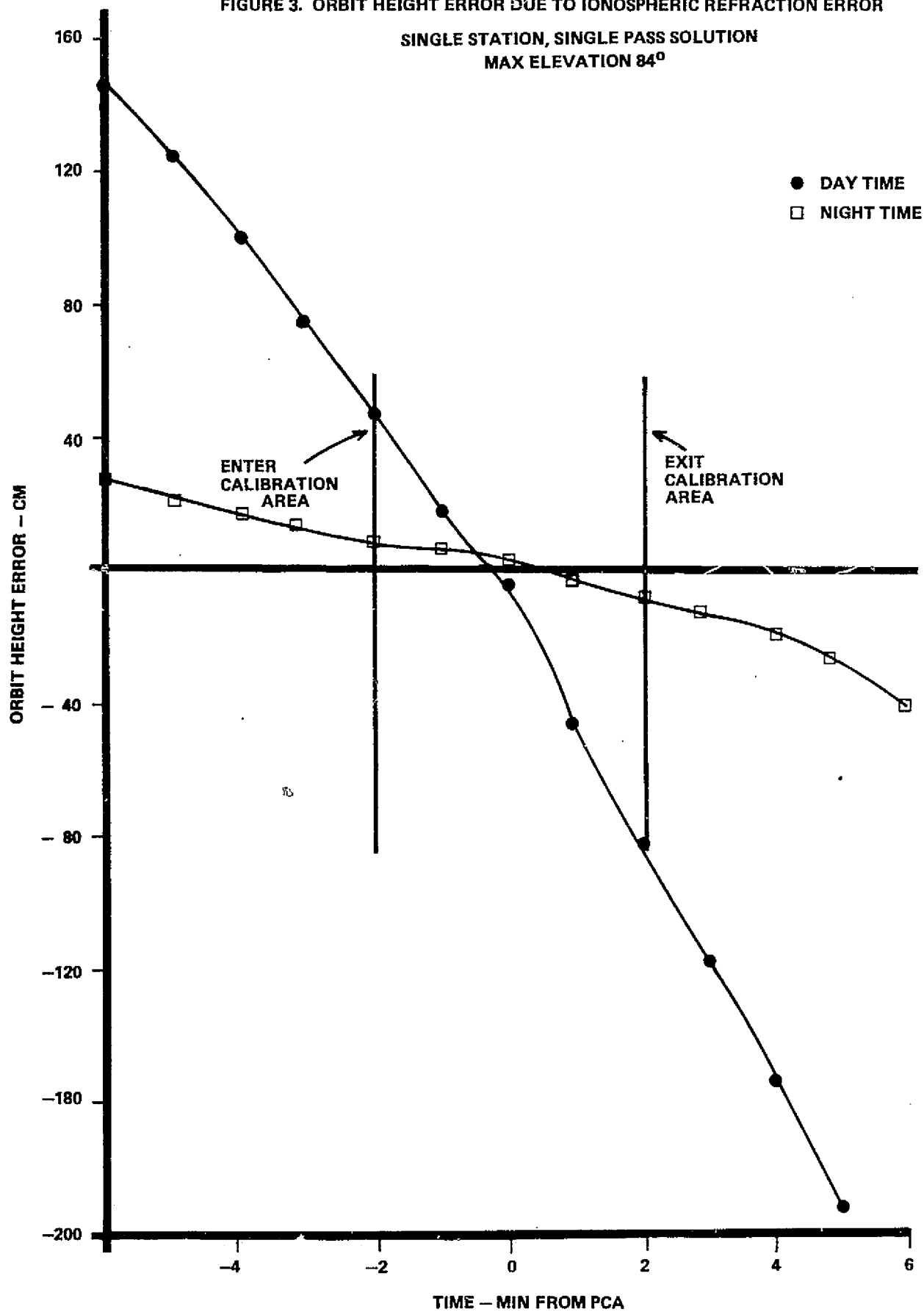


FIGURE 3. ORBIT HEIGHT ERROR DUE TO IONOSPHERIC REFRACTION ERROR

SINGLE STATION, SINGLE PASS SOLUTION

MAX ELEVATION 84°



from obscuring the day-night effect, identical North-South passes were used for both day and night passes. The daytime effect on the orbit reaches a maximum amplitude of approximately 80 cm inside the calibration area, but the average effect for the four minute period within the calibration area is less than 20 cm. The nighttime effect is smaller by about an order of magnitude and averages to near zero.

To illustrate the extent to which propagation errors would be visible in measurement residuals; Figures 4 and 5 show the propagation of tropospheric and ionospheric refraction errors into range residuals. For the 3% tropospheric error, it is seen that the range residuals would be affected by only about 4 cm. A residual effect of the same magnitude could be expected from the ionosphere for the daytime pass. Propagation errors in the residuals from single station, high elevation pass solutions would thus be near impossible to detect.

4.2.2 Multi-Station Orbital Solutions

As an example of a typical multi-station calibration, a North-South GEOS-C pass essentially down the middle of the calibration area was simulated. In this case, only range data was assumed to be used in the orbital solution, and data from all four stations (Bermuda, Wallops Island, Merritt Island, Grand Turk) was equally weighted and assumed to be used down to 10° elevation angle. The calibration area, however, was considered to be bounded by the quadrangle formed by the four stations, and the subsatellite times within this area are indicated on the error propagation curves.

Figure 6 shows the effects on the satellite height of 3% tropospheric refraction errors from each of the four tracking stations. With the errors from the four stations

FIGURE 4. EFFECTS ON RANGE RESIDUALS DUE TO TROPOSPHERIC REFRACTION ERROR
SINGLE PASS, SINGLE STATION SOLUTION
MAX ELEVATION 84°

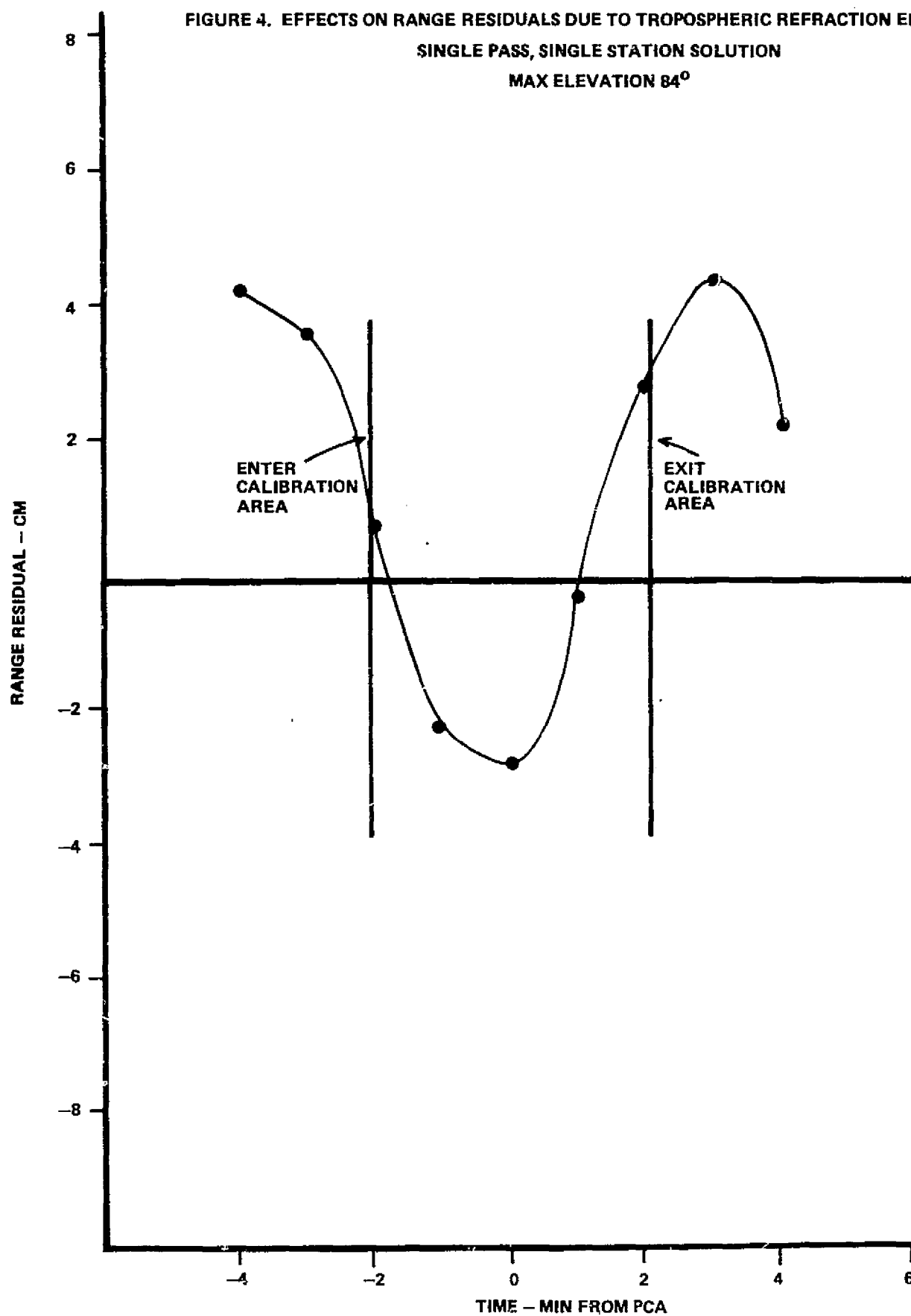
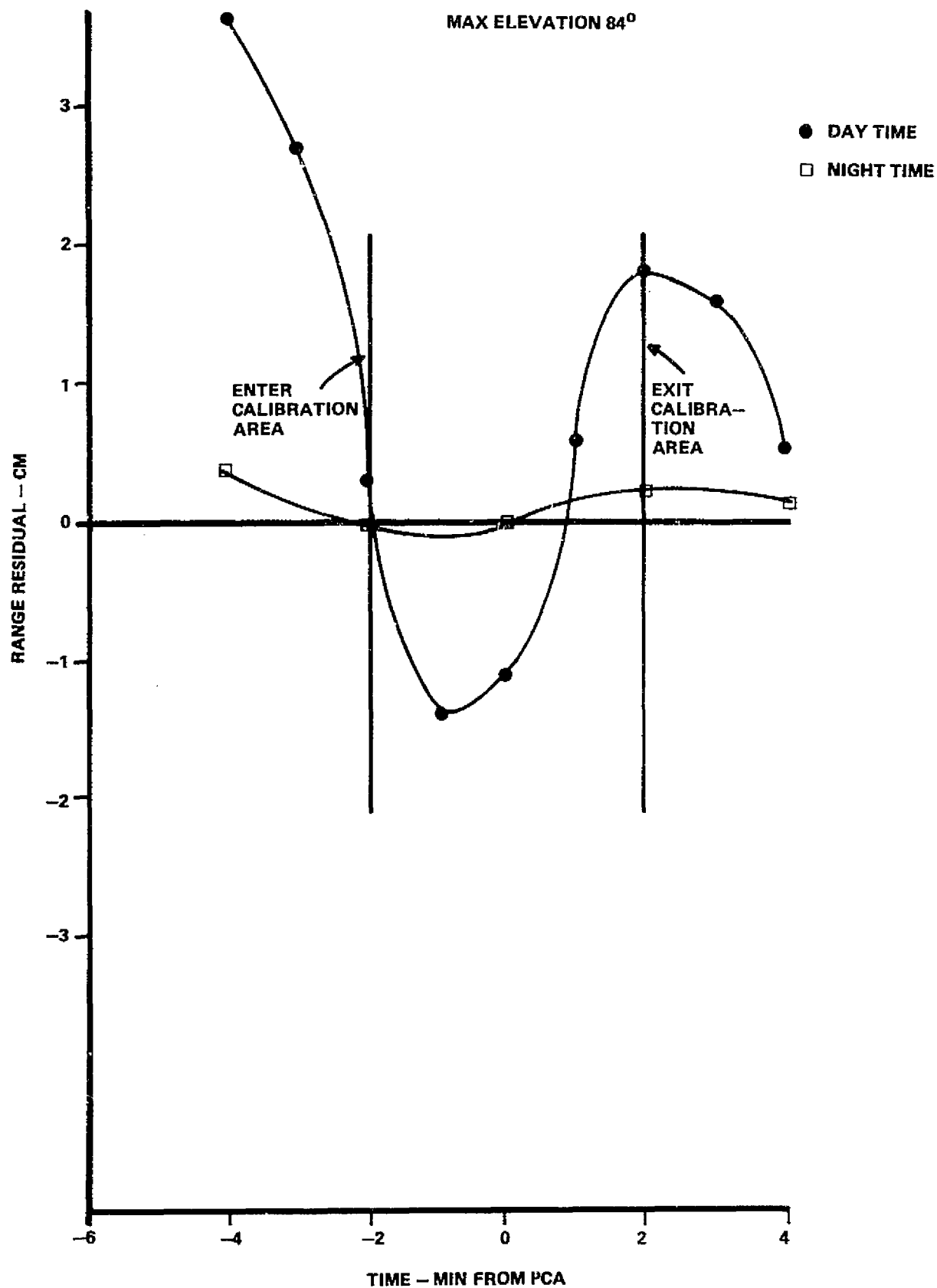
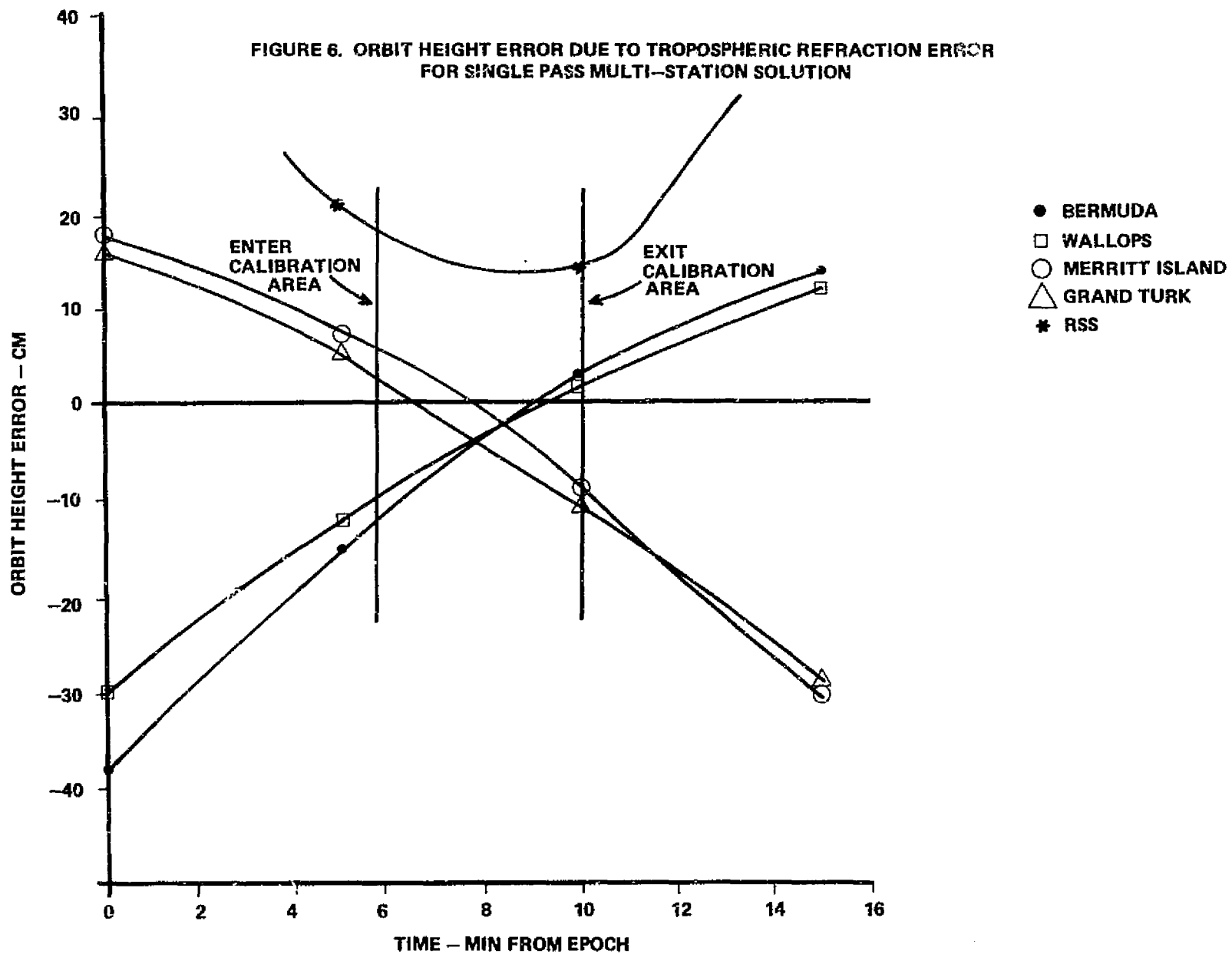


FIGURE 5. EFFECTS ON RANGE RESIDUALS DUE TO IONOSPHERIC REFRACTION ERROR

SINGLE PASS, SINGLE STATION SOLUTION

MAX ELEVATION 84°





considered to be independent, the total standard deviation due to tropospheric refraction is also shown. The total error is on the order of 15-20 cm. For a pass through the calibration area, these numbers may be somewhat pessimistic and do not properly account for the averaging out of error effects. Note, for example, that the Merritt Island effect, within the calibration area, averages to near zero.

Orbit height error due to the ionosphere for the same multi-station solution is shown in Figure 7. The average effect within the calibration area for the daytime pass is approximately 40 cm, dropping to less than 10 cm at night. Consistent with the tropospheric sign convention, the curves plotted are for the application of a correction which is too large. Since the neglect of the ionosphere amounts to making a correction which is too small, the average orbit altitude through the calibration area for a mid-day pass will be too high by about 40 cm when the orbit is obtained by C-Band range tracking.

The range residuals at each of the four tracking stations will have components due to errors at all stations. Figure 8 shows the effects on the Bermuda range residuals due to both tropospheric errors at Bermuda, and to errors at Merritt Island. The residual effects are somewhat larger than the associated effects on the orbit, but probably are still not detectable in actual residual patterns.

Curves for the effects of the ionosphere on Bermuda residuals, for both day and nighttime passes, are shown in Figure 9. Amplitudes for the daytime pass are comparable to those for tropospheric effects. For neglect of the ionosphere, the actual residual sign should be the negative of the curves shown.

FIGURE 7. ORBIT HEIGHT ERROR DUE TO IONOSPHERIC REFRACTION ERROR
SINGLE PASS, MULTI-STATION SOLUTION

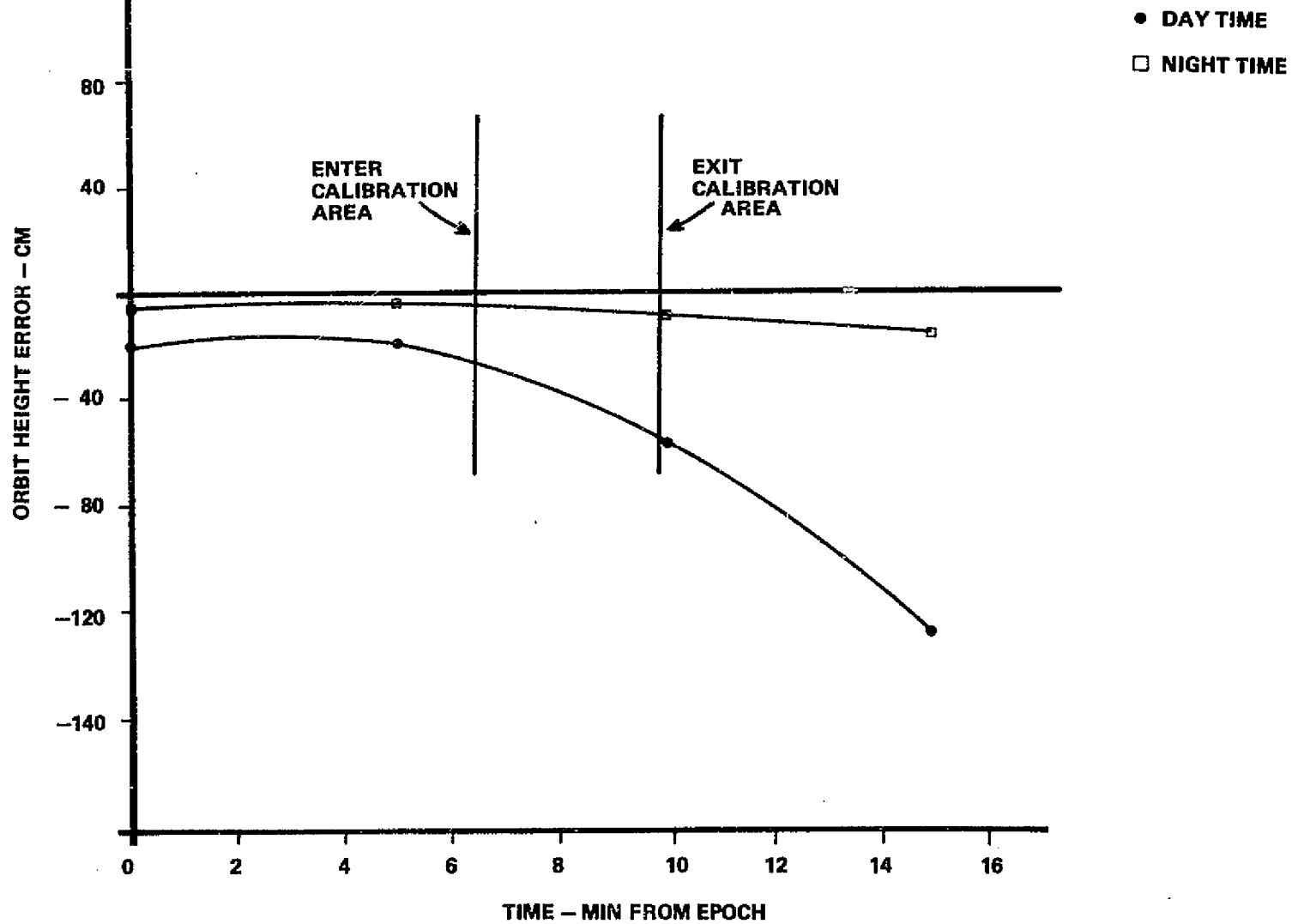


FIGURE 8. EFFECTS OF TROPOSPHERIC REFRACTION ERRORS FROM BERMUDA AND MERRITT ISLAND
ON BERMUDA RANGE RESIDUALS
MULTI-STATION SOLUTION

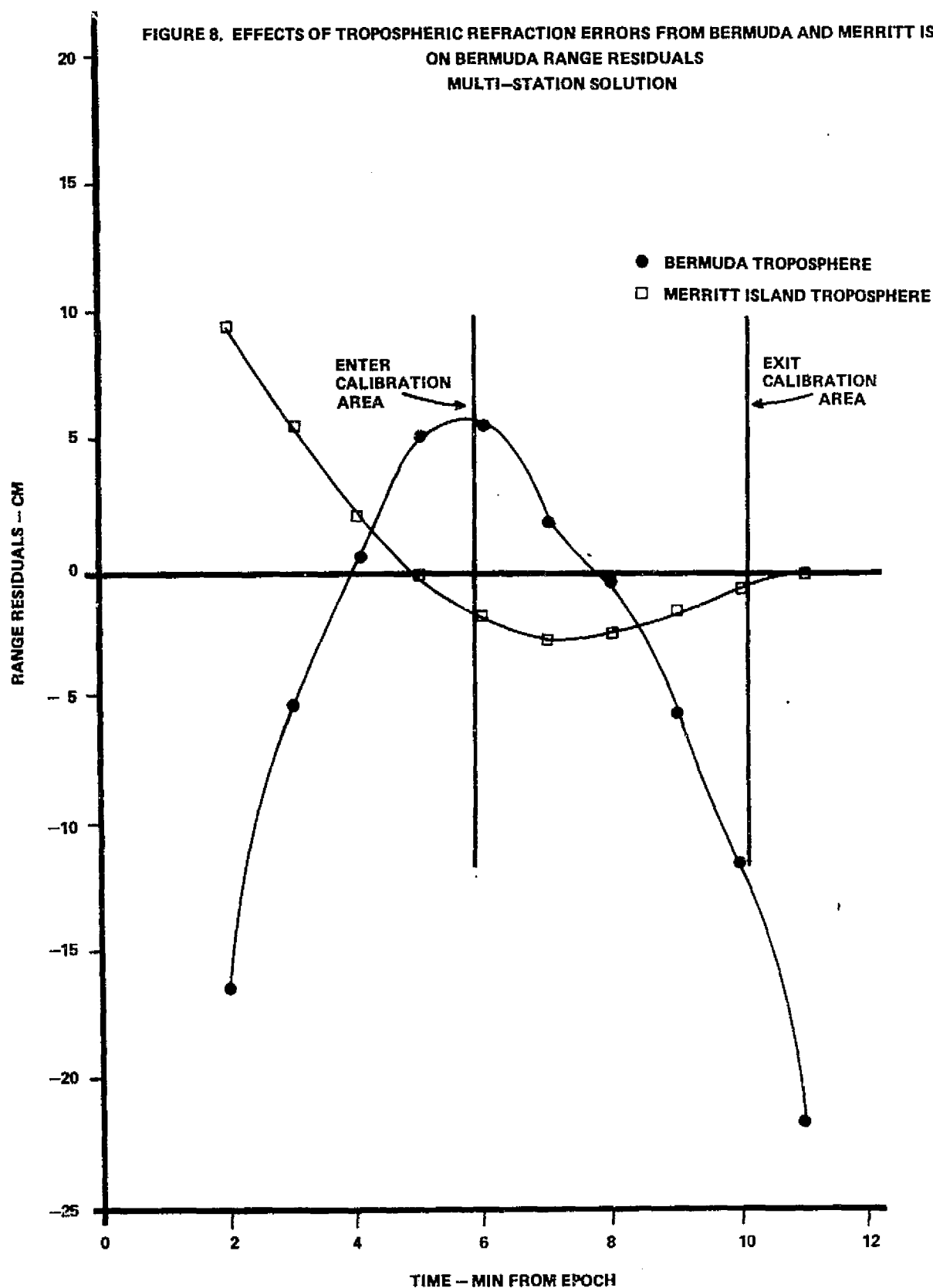
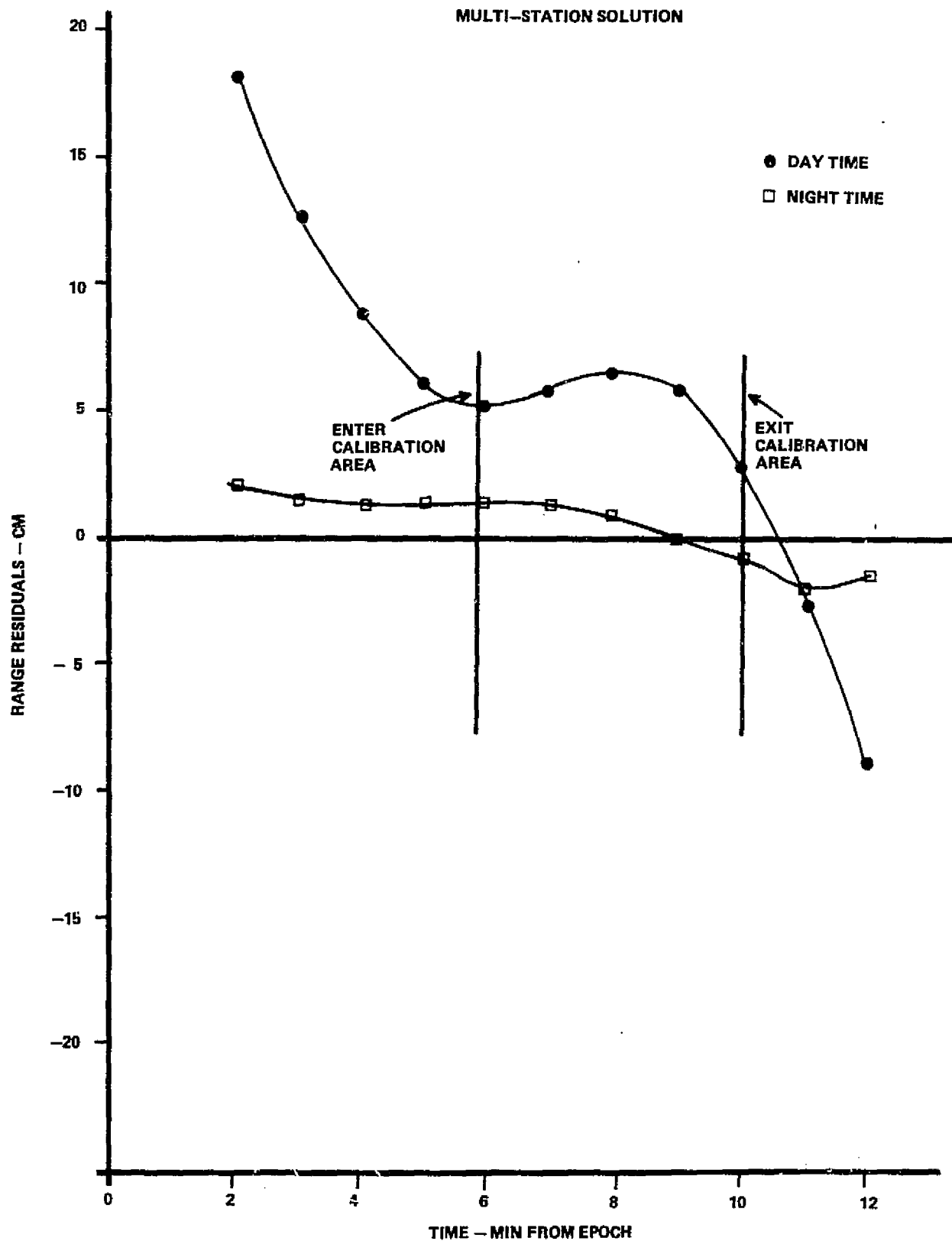


FIGURE 9. EFFECTS ON BERMUDA RANGE RESIDUALS DUE TO IONOSPHERIC REFRACTION ERROR
MULTI-STATION SOLUTION



4.2.3 Stability Comparisons

One of the primary means of assessing altimeter stability will be the comparison of sea surface height measurements at points in the calibration area where two passes of altimeter data cross. Typically for such passes, one will be a daytime and the other a nighttime pass. Figure 6 shows that the height error for each pass will be about 15 cm due to tropospheric errors, and the difference in the effects for different passes would be expected to be approximately 20 cm ($\approx \sqrt{2} \times 15$) on the assumption that the errors are uncorrelated from one pass to the next.

From Figure 7, the difference in the ionospheric effects between day and night would be approximately 30 cm. This should be the maximum difference. Early morning and early evening passes, for example, should be quite similarly affected.

The total contribution of propagation errors to stability comparisons should thus be on the order of

$$\sqrt{(20)^2 + (30)^2} = 40 \text{ cm}$$

with the largest contribution due to the ionosphere. If propagation should make the largest error contribution to stability comparisons, it may be noted that the daytime orbit height will be too large and thus should produce a calculated sea surface height which is too large.

4.3 GLOBAL ORBIT DETERMINATION

Operational GEOS-C orbits for use with altimeter data are planned to be determined using tracking data from one or more revolutions. Two samples of such orbits will be considered.

4.3.1 One Revolution Orbits

As an example of a single revolution orbital solution, a simulation was performed with the following C-Band radar tracking complement:

Munich, Germany	two passes	(~4PM & 6PM local time)
Bermuda	one pass	(~10AM local time)
Wallops Island, Virginia	one pass	(~10AM local time)
Merritt Island, Florida	one pass	(~10AM local time)
Grand Turk	one pass	(~10AM local time)

Considering the tropospheric refraction errors to be independent for the different stations and for different passes, Figure 10 shows the effects on orbit height. The average error is less than 10 cm and does not exceed 15 cm.

As indicated above, the tracking schedule includes mostly daytime tracking, although none takes place at the peak ionospheric period of 12 noon - 2PM. Figure 11 shows the orbit height error due to 100% ionospheric refraction error. The amplitude of the error reaches 40 cm, and the total variation in the orbit height due to the ionosphere is 80 cm. Although some other distribution of tracking data during the revolution could certainly have reduced the amplitude of the ionospheric effect, the curve shown should be representative for typical daytime operational orbits.

Also shown on Figure 11 is the effect of the ionosphere on the altimeter measurement itself and it is seen to be 10 cm or less throughout the revolution. The effect is, of course, always in the same direction and always has the effect of making a measured sea surface height too small.

FIGURE 10. RSS TROPOSPHERIC REFRACTION ERROR IN ORBIT HEIGHT
1 REVOLUTION SOLUTION

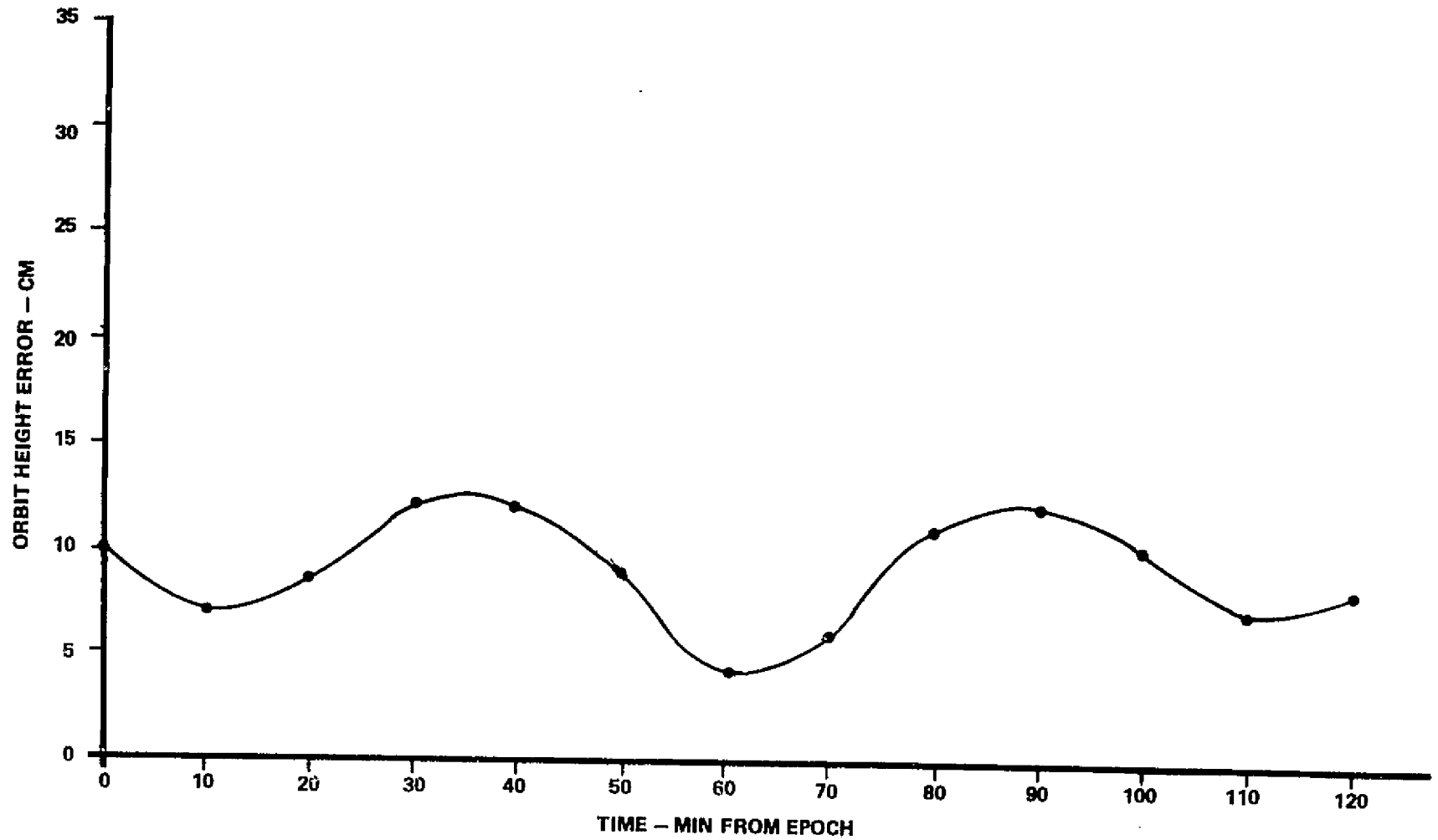


FIGURE 11. EFFECTS DUE TO IONOSPHERIC REFRACTION ERROR
1 REVOLUTION SOLUTION

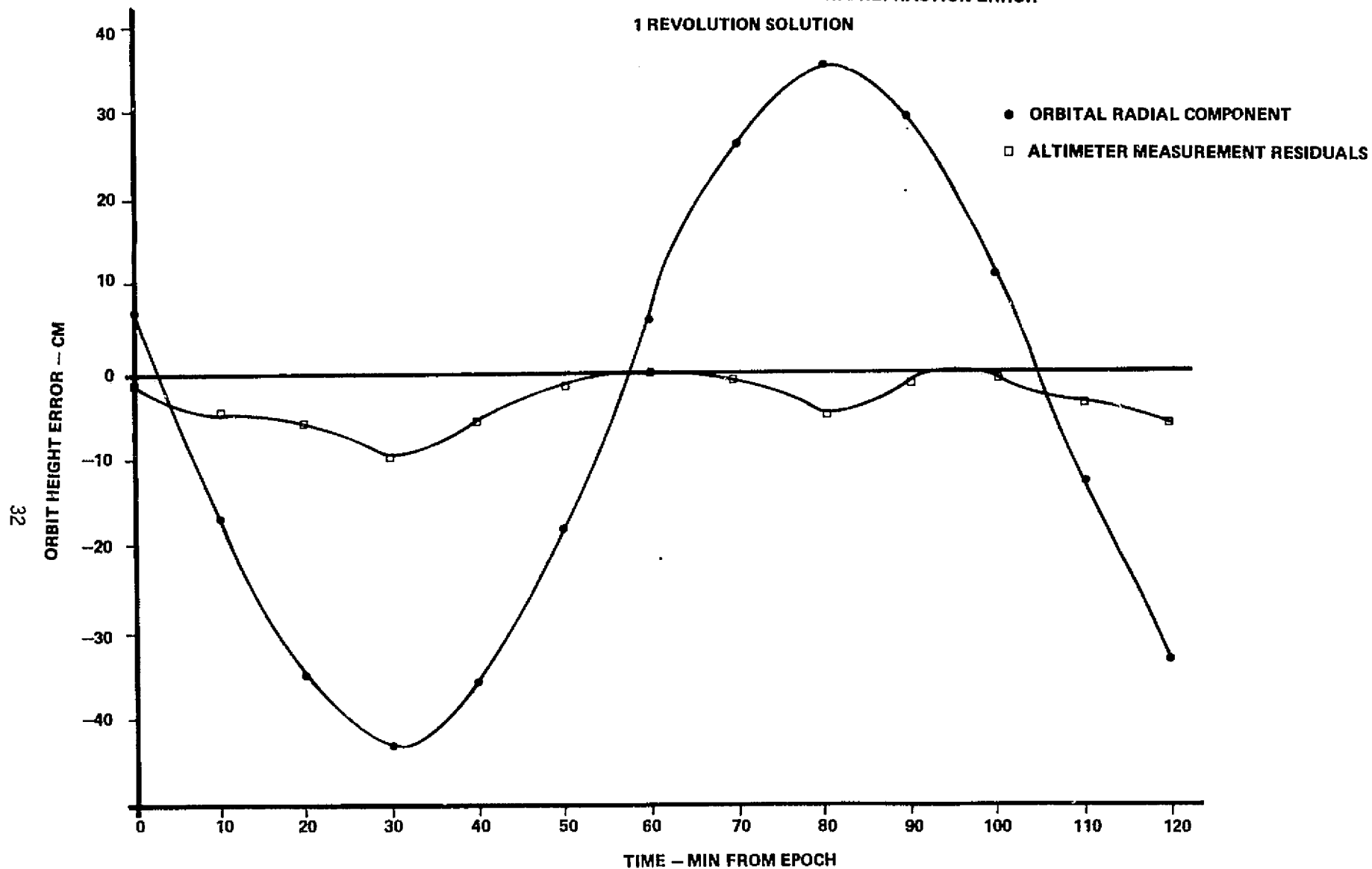
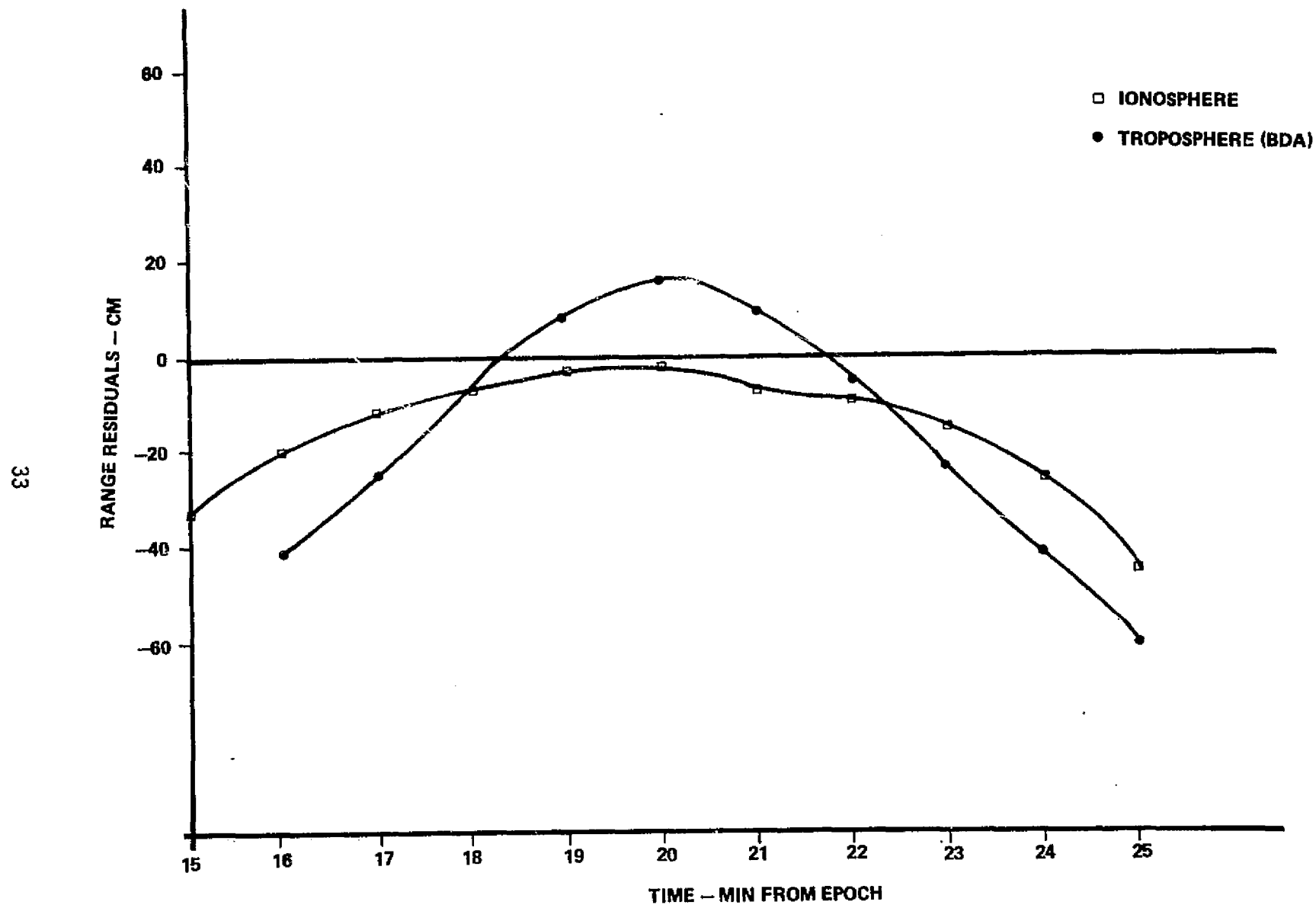


FIGURE 12. EFFECTS OF IONOSPHERIC AND TROPOSPHERIC REFRACTION ERRORS ON BERMUDA RANGE RESIDUALS

1 REVOLUTION SOLUTION



Typical range residuals from one of the five passes in this solution are shown in Figure 12 for both ionospheric effects and the effects of the tropospheric error at Bermuda. At the end of the pass, the tropospheric residual effects exceed 50 cm and should be observable in data reduction residuals (if not obscured by larger effects). The ionospheric effect is almost as large. The effects may, of course, add or cancel depending upon the sign of the tropospheric error.

4.3.2 One Day Orbits

As an example of longer arc lengths, a simulation was performed for a one day set of tracking data, with the following set of tracking stations tracking at any time the spacecraft could be seen above 10° elevation angle:

Munich, Germany	Antigua
Aberporth, England	Grand Turk
Wallops Island, Virginia	White Sands, N.M.
Bermuda	Tananarive, Madagascar
Merritt Island, Florida	Pillar Point
Fly, Nevada	Canton Island
Kauai, Hawaii	Woomera, Australia
Ascension Island	Carnarvon, Australia

Daytime and nighttime passes were, of course, included in this set of tracking for all stations.

The orbit height error due to tropospheric refraction errors at all the tracking sites is shown in Figure 13, in which the contributions from the different stations have been combined on the assumption that the errors at the different sites are independent. Only the first six hours are shown, since the error has primarily a once per revolution

**FIGURE 13. EFFECTS ON ORBIT HEIGHT DUE TO TROPOSPHERIC
REFRACTION ERROR (RSS)
1 DAY SOLUTION**

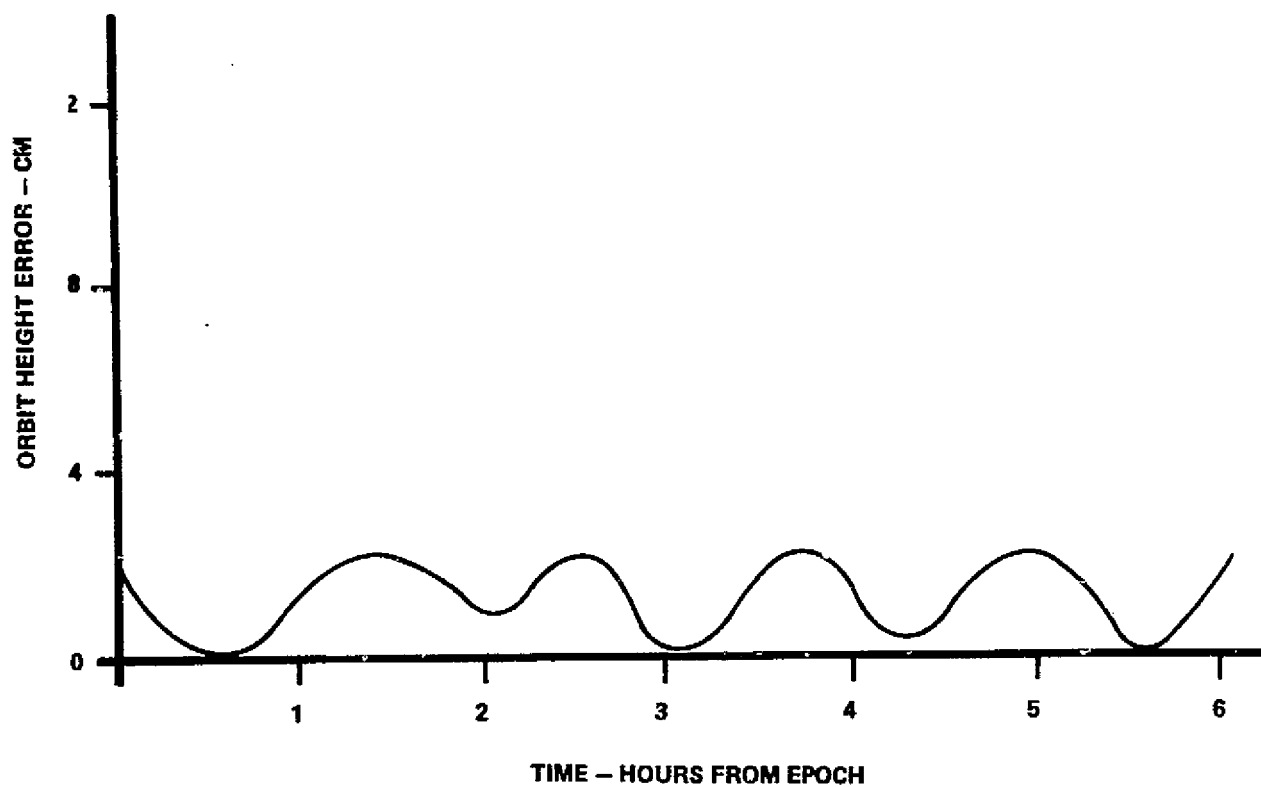
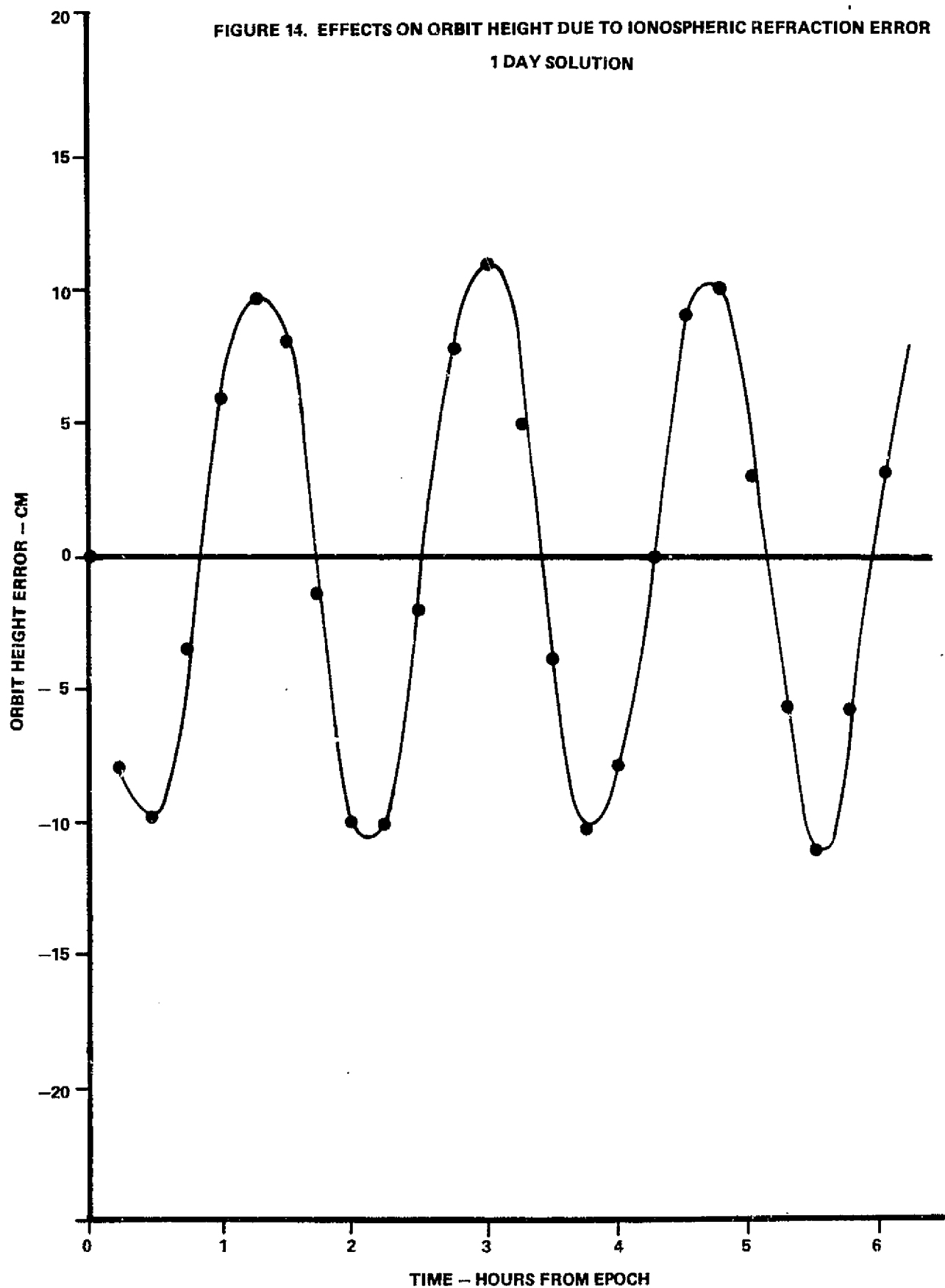


FIGURE 14. EFFECTS ON ORBIT HEIGHT DUE TO IONOSPHERIC REFRACTION ERROR
1 DAY SOLUTION



variation. The maximum error is seen not to exceed 2 cm. Thus, as had been anticipated, the troposphere is not a significant error source for long arcs. Since the orbit is virtually unaffected, measurement residuals should reflect the full refraction error and no residual effects have been graphed.

Figure 14 shows the effects of ionospheric refraction on the orbit height error for the one day orbital solution. Again, only the first six hours are shown since the variations are similar throughout the full day during which tracking occurs. The error appears very nearly sinusoidal with an amplitude of 10 cm and the period of the orbit.

4.4 CROSS TRACK AND ALONG TRACK ORBIT ERRORS

The primary orbit component of concern for GEOS-C is the radial component. Large orbit errors in the other orbit components would, however, not be tolerable and several curves have been included to show the effects of the propagation errors in the cross track and along track directions.

Figure 15 shows the effects of tropospheric refraction errors on the four station single pass solution through the calibration area. Effects due to the ionosphere are shown in Figure 16 for both daytime and nighttime tracking. All errors are definitely at the sub-meter level.

Figure 17 shows the effects of tropospheric refraction errors on the one revolution solution from the tracking by four stations (two passes for one station), and Figure 18 shows the ionospheric effects on the same orbit. Ionospheric effects are somewhat larger, slightly exceeding the one meter level.

FIGURE 15. ALONG TRACK AND CROSS TRACK ORBIT ERROR DUE TO TROPOSPHERIC REFRACTION ERRORS (RSS)
MULTI-STATION, SINGLE PASS SOLUTION

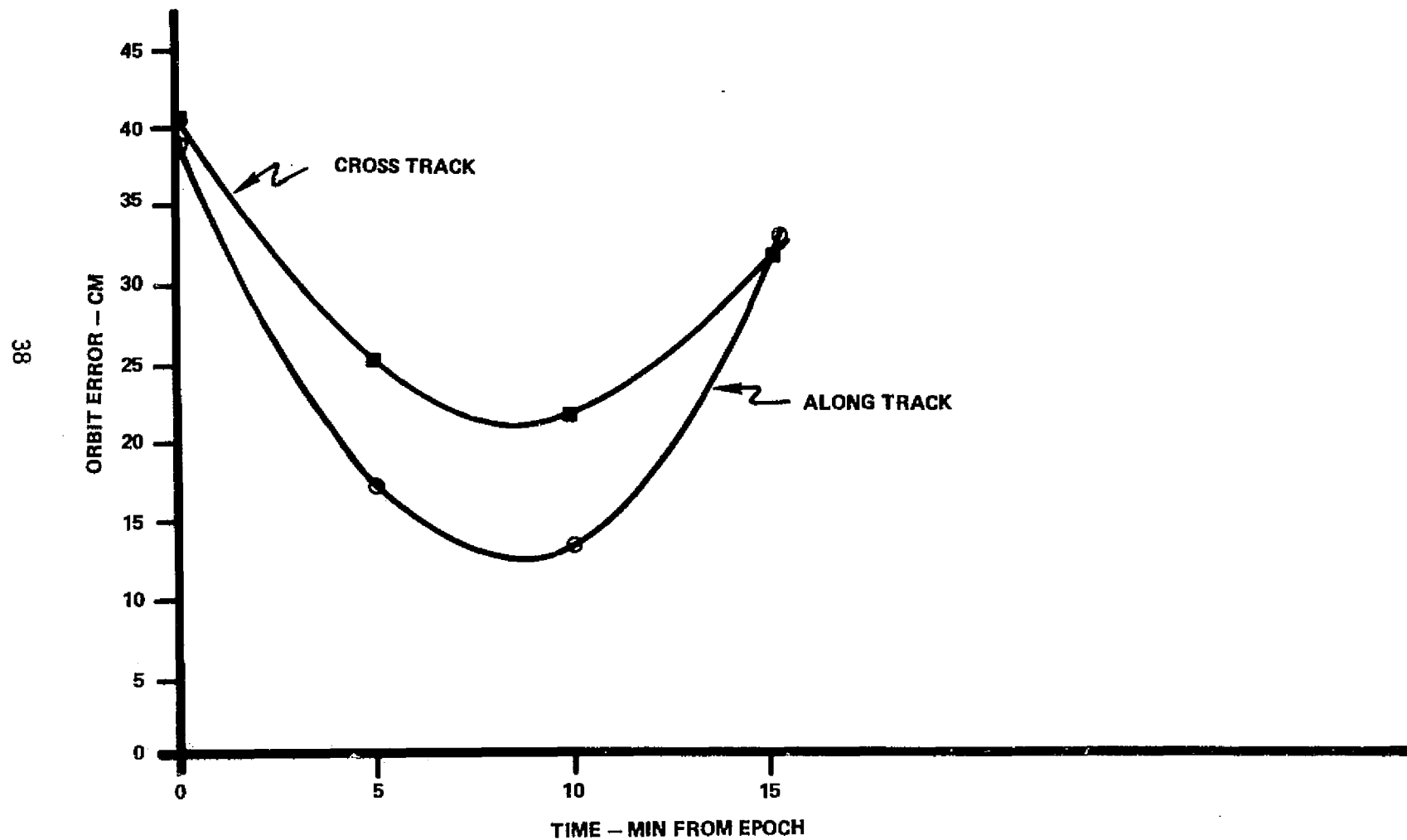


FIGURE 16. ALONG TRACK AND CROSS TRACK ORBIT ERROR DUE TO IONOSPHERIC REFRACTION ERROR
MULTI-STATION, SINGLE PASS SOLUTION

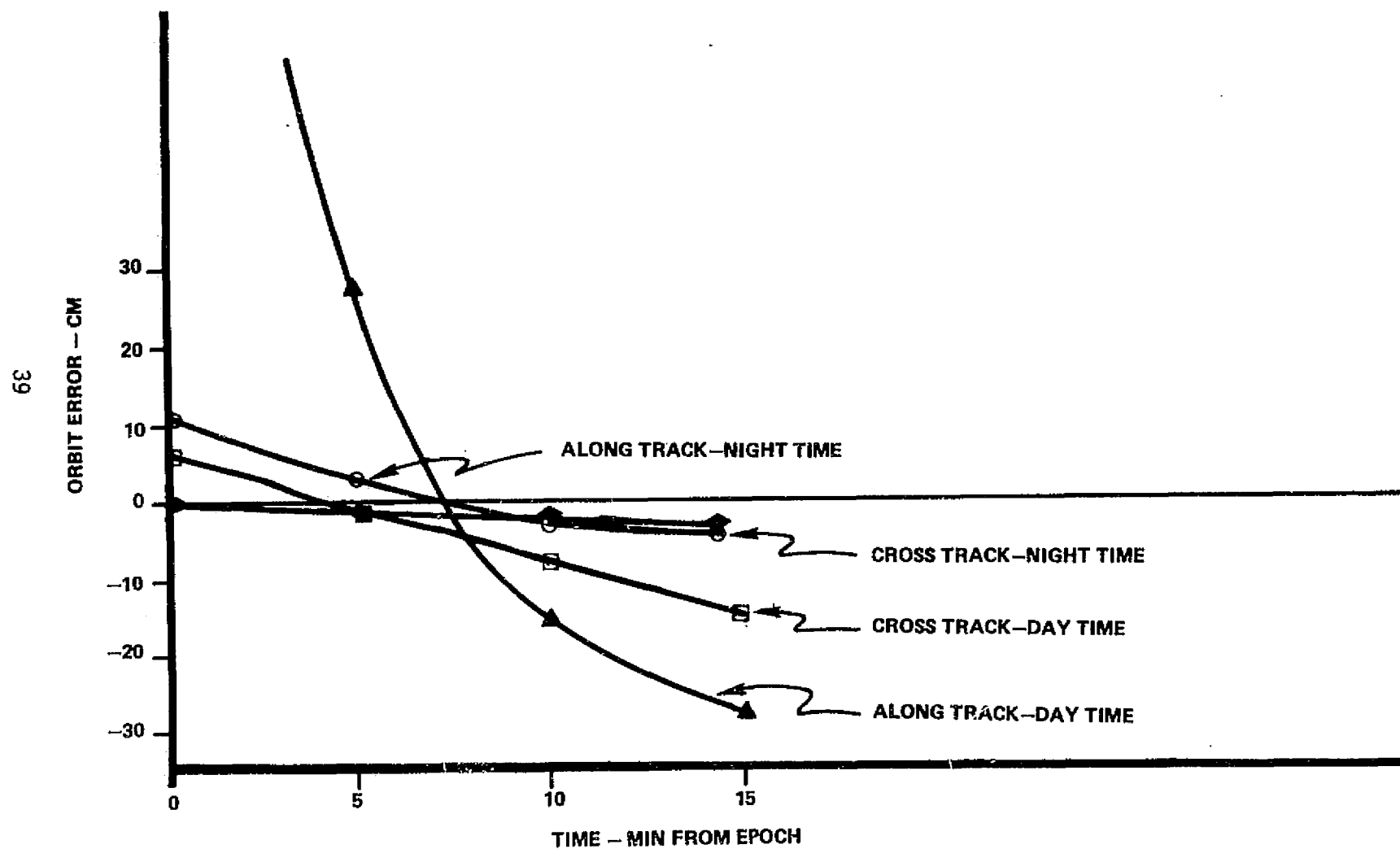


FIGURE 17. ALONG TRACK AND CROSS TRACK ERROR DUE TO TROPOSPHERIC REFRACTION ERRORS (RSS)
1 REVOLUTION SOLUTION

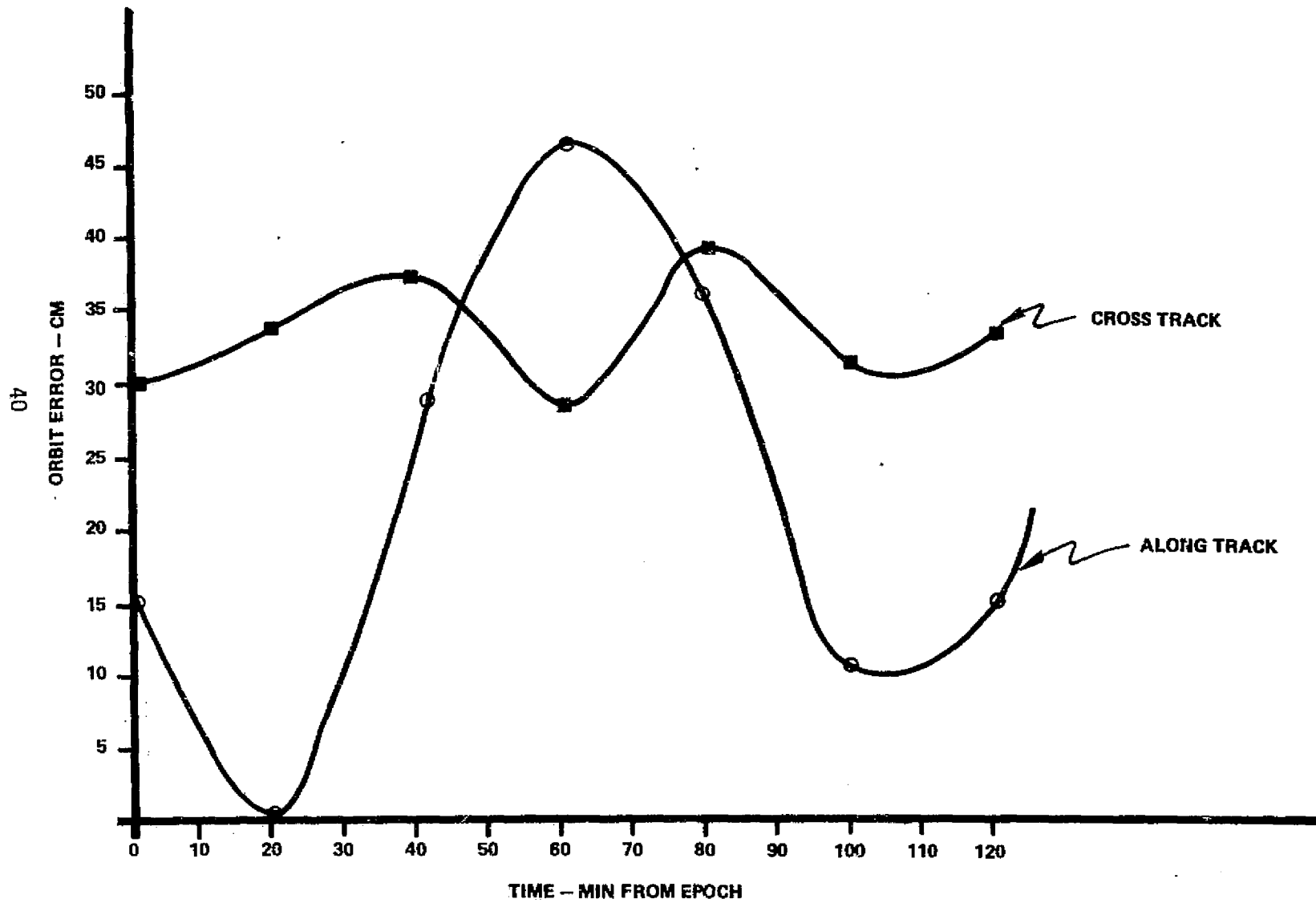
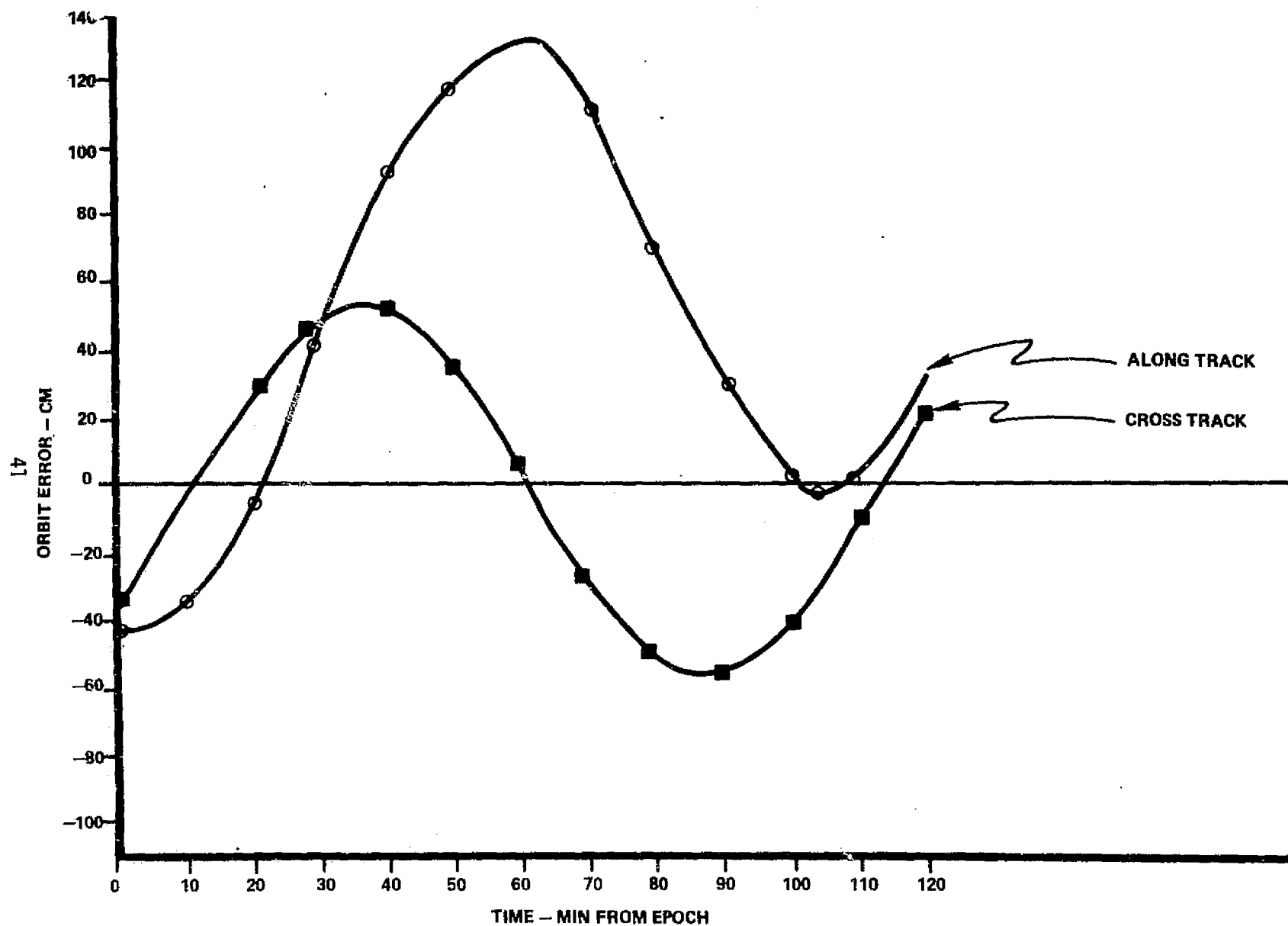


FIGURE 18. ALONG TRACK AND CROSS TRACK ERROR DUE TO IONOSPHERIC REFRACTION ERROR
1 REVOLUTION SOLUTION



SECTION 5.0

EXTRAPOLATION OF IONOSPHERIC EFFECTS

The error analyses of the previous section for ionospheric effects have been based on predicted solar activity for April 1975. Electron densities in the ionosphere are approximately proportional to solar flux and, as shown in Figure 1, solar flux is near its 11 year minimum at about this time. After 1976, solar flux values will begin to grow until the peak is reached in 1982. Based on past data, the peak solar flux value to be expected is about 143.

In section 4, the ionosphere was found to produce orbit errors in a one revolution solution with an amplitude of approximately 40 cm. The corresponding amplitude of the effect on the altimeter measurement itself was approximately 10 cm. Extrapolating these numbers based on predicted solar flux values for the next several years, we obtain the results shown in Figure 19 for orbit error and in Figure 20 for the altimeter measurement error. The errors increase almost linearly from a minimum around the end of 1975 and almost double by 1980. The predicted 1980 effects are thus approximately 80 cm for orbit error from a one revolution orbit determination and 20 cm for the altimeter measurement error. As we have also seen in the previous section, the orbit error can be drastically reduced through the use of longer arcs. A one day arc has errors due to the ionosphere which are only 25% of those for the one revolution arc. The effect on the altimeter cannot, of course, be so reduced and effects on the order of 20 cm may be expected. Since the full amplitude of this variation may be seen in much less than a revolution, profiling errors that are significant may also result for post-GEOS-C altimeters.

**FIGURE 19. MAXIMUM RADIAL POSITION UNCERTAINTY DUE TO IONOSPHERIC REFRACTION
1 REVOLUTION SOLUTION**

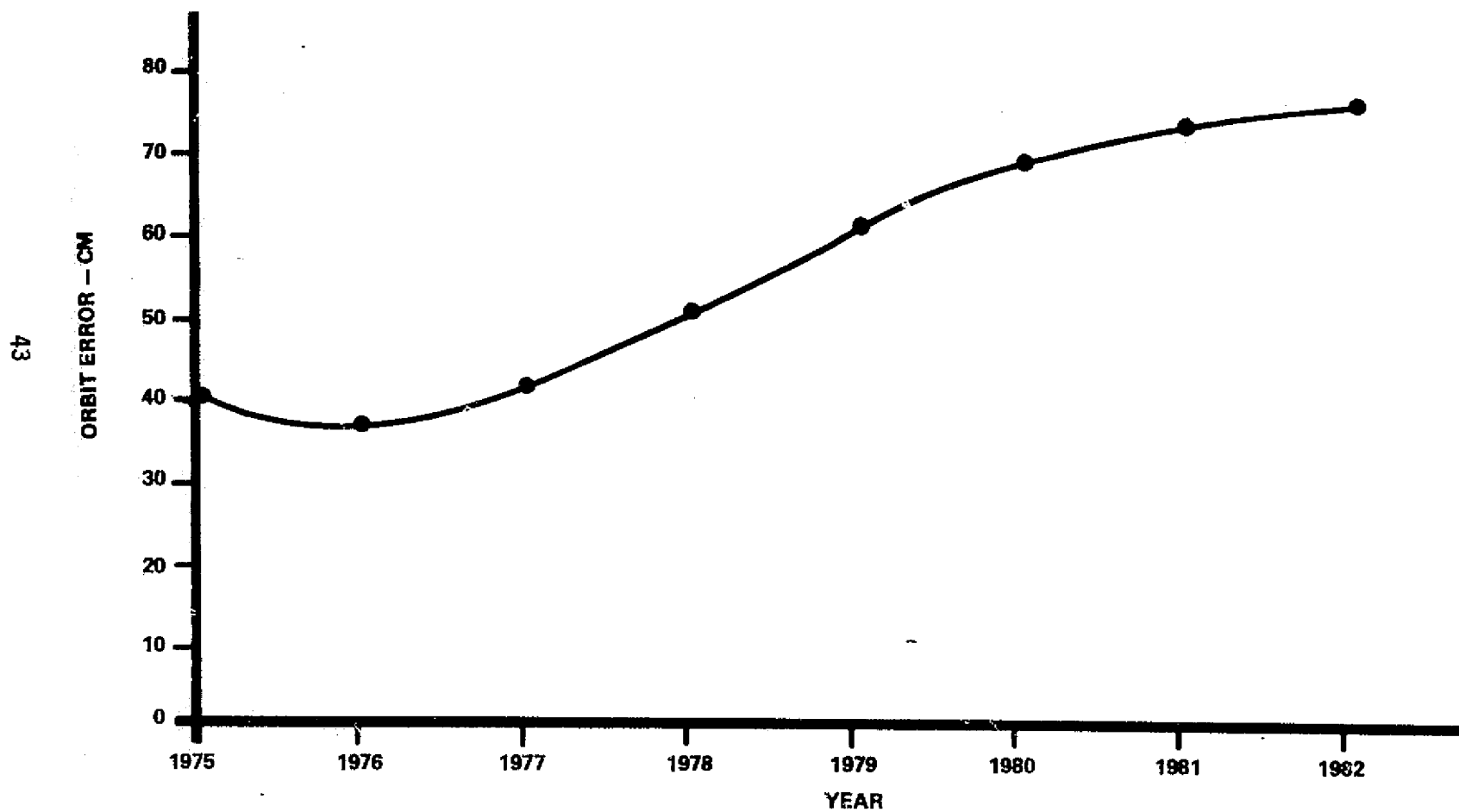
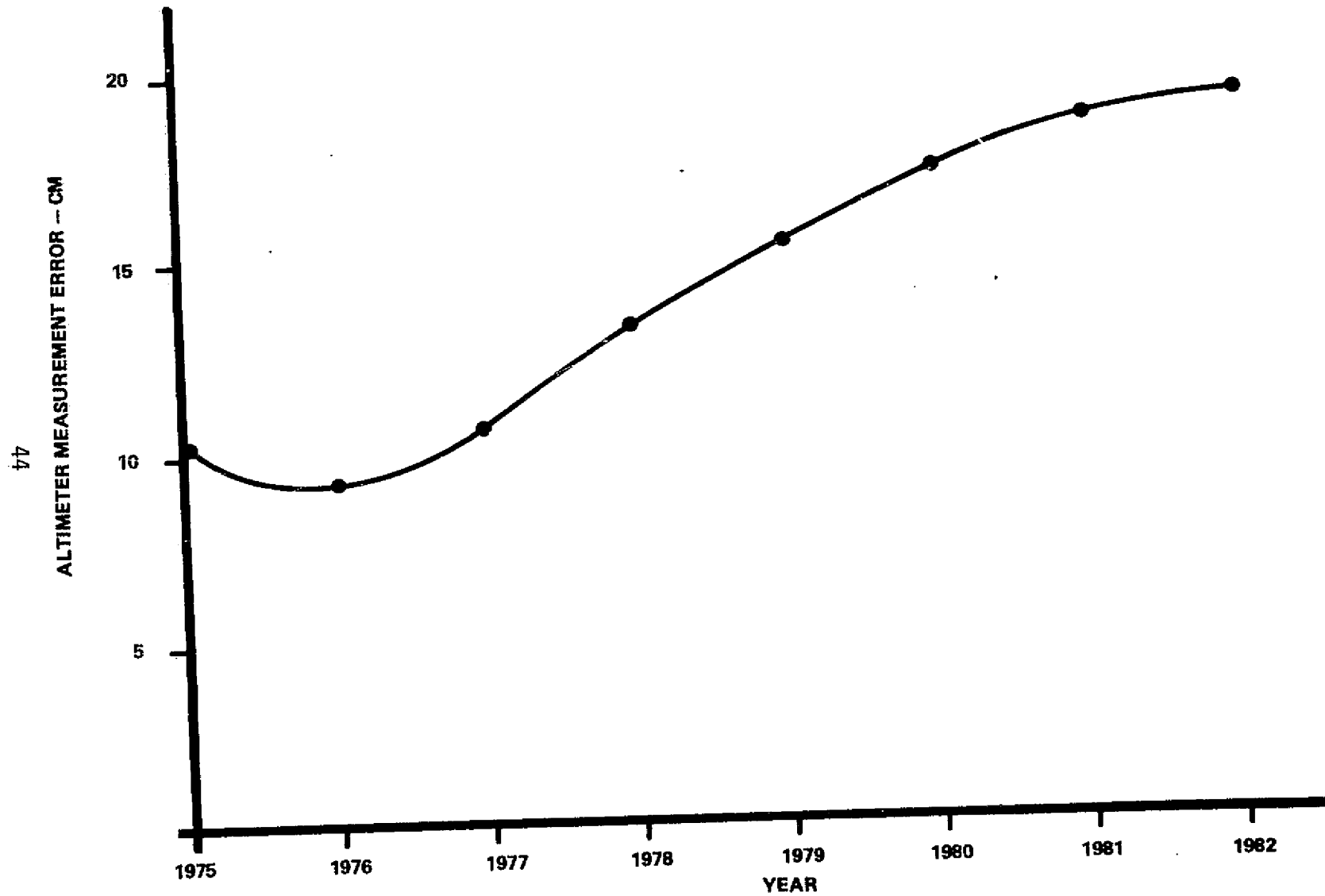


FIGURE 20. MAXIMUM ALTIMETER ERROR DUE TO IONOSPHERIC REFRACTION
1 REVOLUTION SOLUTION



SECTION 6.0

SUMMARY AND CONCLUSIONS

Propagation errors have been considered in terms of planned procedures for GEOS-C and the appropriate level for propagation errors in the altimeter error budget if these procedures are followed. The procedures may be summarized as follows, with the basic measurement instrument for orbit determination assumed to be C-Band radars:

1. Use a tropospheric refraction correction method (modified Hopfield) requiring input of surface values of temperature, pressure and humidity.
2. For ground stations, use recorded meteorological data when available, and a default station independent set of meteorological parameters when this data is unavailable.
3. For the altimeter, use surface meteorological parameters based on monthly means which are functions of latitude.
4. Make no corrections for ionospheric effects.

Table 5 summarizes the levels of residual error when these procedures are followed for different types of altimeter missions, based on the error analysis results of Section 4. For the troposphere, the numbers listed are for the use of surface meteorological measurements for all tracking stations, and no use of the default model. Ionospheric effects are the full effects of the ionosphere as predicted by the Bent ionospheric model.

Type of Mission	Orbit Type	Tropospheric Residual Error	Ionospheric Effects
Calibration	Single Pass, Multi-station	15 cm	40 cm (daytime) 5 cm (nighttime)
Global Geoid	One Revolution, Multi-Station	10 cm	40 cm
Global Geoid	One day, Multi-Station	2 cm	10 cm
Altimeter Measurement		10 cm	10 cm

Table 5. Summary of Levels of Propagation Errors on GEOS-C Altimeter Missions

Based on the results of Table 5 and the conditions under which they were determined, the following conclusions may be drawn as to the effects to be expected from propagation errors under different correction procedures:

1. Tropospheric Refraction Effects on Orbits

As expected, tropospheric refraction error effects decrease with increasing arc length, going from 15 cm for a single pass orbit to 2 cm for a one day orbit. The errors propagated are 3% of the actual correction, with 2% error being possible with negligible error in the surface meteorological data and almost 10% error to be expected if no actual data is available. For the one revolution orbits expected to be used for GEOS-C, this means that tropospheric propagation errors can be reduced to ~7 cm with good surface data, and may be as large as 30 cm with no surface data available. Reduction below 7 cm for radar data would require the use of atmospheric measurements, such as from radiosondes, and the use of ray tracing procedures for refraction corrections.

2. Tropospheric Refraction Effects on Altimeter Data

The use of monthly averages of surface values of meteorological parameters is sufficient to reduce the residual error to 10 cm. A reduction to approximately 5 cm would be possible with the use of surface data. Reduction below the 5 cm level would require the use of atmospheric data from regions other than the surface.

3. Ionospheric Refraction Effects on Orbits

Ionospheric effects are also decreasing functions of arc length. For the planned one revolution orbits, the effects are at the 40 cm level in amplitude, with peak to peak variations of 80 cm. This effect can be reduced somewhat through the use of nighttime tracking data whenever possible. It can also be reduced by about a factor of two through the use of an ionospheric model (such as the one used for the error propagations). Further reduction would require the use of ionosondes or dual frequency tracking data. Note too that ionospheric errors will increase by a factor of two within the next six years.

4. Ionospheric Refraction Effects on Altimeter Data

As shown in Figure 11, ionospheric effects reach an amplitude of about 10 cm on the 13.9 GHz altimeter range measurement and this value will increase to about 20 cm in 1980. Again, a reduction by at least a factor of two is possible using a global ionospheric model, and any further reduction would require the use of ionospheric measurements on the day data was taken.

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